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A Study on the Eigenmodes in the Photonic Crystal Waveguide with Dielectric Hole

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ABSTRACT

The eigenmodes in the photonic crystal Waveguide with dielectric hole are investigated by finite element method. The relative permittivity of the dielectric hole and cladding is significantly lower than that of the core areas. The propagating wave is confined in the region of the high relative permittivity by Snell's law. The space of the waveguide is divided into the elementary triangular mesh in the process of numerical calculation. The Krylov-Schur iteration method is performed to obtain several prominent and reliable eigenmodes. The eigenmode obtained from this calculation is determined as the transverse electro-magnetic modes because the photonic dielectric hole mixes the transverse magnetic and transverse electric characteristics. As results, eigenmodes composed with the vector electric field, three-dimensional electric potential and two dimensional electric equipotential are shown in a simple schematic representation. These results will enable the implementation of more advanced communication fiber by utilizing the ideal properties of the photonic crystal waveguide.

Keyword: permittivity, waveguide, eigenmode, finite element method, Krylov-Schur iteration method, Transverse Electro-Magnetic, communication.

INTRODUCTION

Previously, we have studied on the eigenmodes established in the PCWDH (Photonic Crystals Waveguide with Dielectric Hole) of various types using FEM (Finite Element Method) [1][2][3]. In these studies, air or dielectric holes were arranged symmetrically according to the geometry of the photonic crystal waveguide [3]. As is well known, photonic crystals have the property of being able to confine electromagnetic waves to a certain area and control eigenmodes according to the spatial arrangement of dielectric holes [3]. The main purposes of those studies were to identify the eigen-properties of the photonic crystal waveguide influenced by the dielectric holes. The cross-sectional area of the waveguide was square and circular form, and the dielectric holes of photonic crystal were arranged symmetrically around the core. However, previous studies have shown results that do not meet wanted precise characteristics of eigenmode, and further developing efforts have been required. Comparing to conventional coaxial waveguides, the eigenmodes are similar overall but exhibit unwanted diffusing and confusing fields. It has been necessary to attempt to find the most desirable eigenmode by changing the structural properties of the waveguide or varying the dielectric constant and performing repeated virtual experiments. Through this process, the desiring eigenmode can be obtained by finding ideal waveguide conditions that cannot be obtained analytically. So, basing on previous attempts, the structure of the photonic crystal is slightly modified. And the dielectric constant is made significantly different for each region to accomplish this purpose.

In this study, FEM is carried out to investigate the eigenmode established on the cylindrical waveguide of the holes assisted photonic crystal. The cross-sectional space of the waveguide is divided into three regions of the core, cladding and photonic dielectric hole. For FEM numerical calculation, each region is decomposed into the mesh of triangular elements and continuously connected to other areas. The components used to construct the eigenmode are the edges and nodes of a triangle element. In order to improve the resolution of the eigenmode, the number of triangular elements must be large. In this case, improved resolution in eigenmode can be expected, but it is difficult to process this with the limited capacity of a personal computer. Therefore, in this study, to overcome this problem, the Arnoldi algorism is adopted to compress the eigen-matrix equation. Then, several prominent eigenmodes are obtained using the Krylov-Schur iteration method. The eigenmode pairs obtained in this way are largely divided into an electric field vector and an electric potential scalar established with edges and nodes of triangular element respectively. As results, these eigenmodes are described with brief schematic representation. The mathematical derivation process for FEM has been mentioned in a previous manuscript [1][2][5][6][7]. Therefore, this process is not mentioned again in this manuscript. In other words, the theory of FEM is omitted in this manuscript. The describing format of this manuscript is explained as follows, out of the conventional order. This manuscript describes the structure of waveguide for FEM calculation, the result and discussion of the simulation, and conclusion in orders.

THE STRUCTURE OF PCWDH

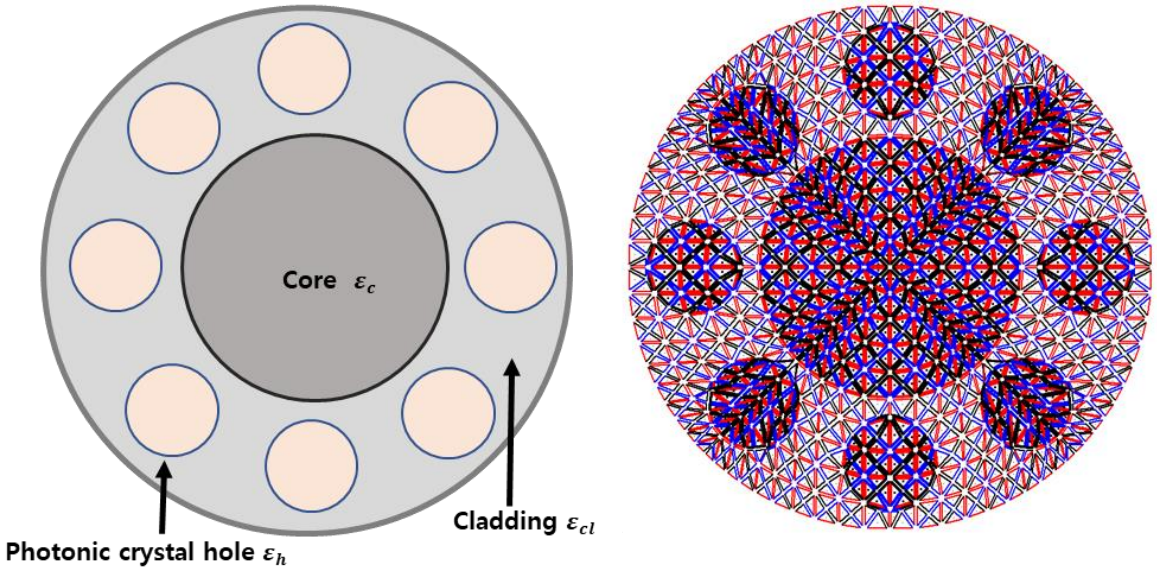


Figure 1: Schematic representation of the HAWDH

As mentioned in the previous study, the eigenmodes depend on the position and relative dielectric of the dielectric holes in the photonic crystal. Dielectric holes can have a negative or positive effect on eigenmode construction depending on the characteristics of the waveguide. In general, dielectric holes have a lower relative permittivity than surrounding space in the waveguide, so shielding propagating electromagnetic waves. So, the dielectric holes in a waveguide are arranged symmetrically around the core to prevent the eigenmodes from being biased to one side in space. In this case, the dielectric hole collects electromagnetic waves to

the center of the core and has a positive effect on forming the eigenmode. In addition, the relative dielectric constants of the cladding and dielectric hole are made to have a low value than the core. The values of dielectric constant composing PCWDH form the relationship $\varepsilon_{cl} < \varepsilon_h \ll \varepsilon_c$. Electromagnetic waves propagating is expected according to Snell's law to establish various types of symmetric eigenmodes around the core. If it is a normal mode, the cladding and the dielectric hole focuses the electromagnetic wave on the core. In this process, the cladding and the dielectric hole form a modified eigenmode, unlike a conventional coaxial waveguide in which only the cladding exists.

To perform FEM calculations, the cross section of the waveguide was decomposed into a mesh consisting of triangular elements. The eigen matrix equation consists of the sides and vertices of triangular elements. These are expressed as vectors and scalar values, respectively, and represent the electric field components and potentials represented by the eigenmodes. The eigenmode is obtained by forming a triangular up diagonalization of the Schur format through similar transformation of this eigen-matrix equation. The diagonal components of the Schur matrix represent eigenvalues, and the similarity transform matrix describes the eigenmodes corresponding to each eigenvalue. In this study, eigenvalues cannot be given physical meaning because the size and structure of the waveguide were changed to take the eigenmode in its most ideal form. Although relative comparison of eigenvalues has no physical meaning, the characteristics of a waveguide can be physically traced using only eigenmode pairs. The eigenmode pairs obtained in this study are the spatial distributions of electric field vectors and potential scalars. In the similarity transformation matrix, vector electric field and scalar potential components of eigenmodes appear simultaneously. The electric field vector is composed with the edge components of the triangular element and plotted in the barycentric point of it. The electric potential is obtained by extrapolating the similarity transform matrix components corresponding to the nodes of the triangular elements [4]. In this study, these eigenmodes were schematically organized into two-dimensional electric field, three-dimensional electric potential, and electric equipotential contours.

The eigenmode obtained numerically by FEM are analyzed with TEM (Transverse Electro-Magnetic) modes. This is because the relative permittivity of the cladding and dielectric hole is significantly smaller than that of the core. These regions establish the eigenmodes different from that of homogeneous cylindrical waveguide. Even though the cladding and dielectric holes are arranged symmetrically around the core, they impose structural heterogeneity in the radial and azimuth directions compared to a homogeneous cross section. Dielectric holes also cause variations in the eigenmode formation of the coaxial waveguide. And, the influence of the waveguide surface that distinguishes TM (Transverse Magnetic) and TE (Transverse Mode) mode causes these modes to mix each other [6]. As for the eigenmodes, TM or TE modes may be dominant, but when these characteristics are mixed, it is understood that the characteristics shown in the conventional coaxial waveguide are modified. Therefore, it is appropriate to apply TEM mode for the analysis of the obtained spectrum.

RESULT AND DISCUTION

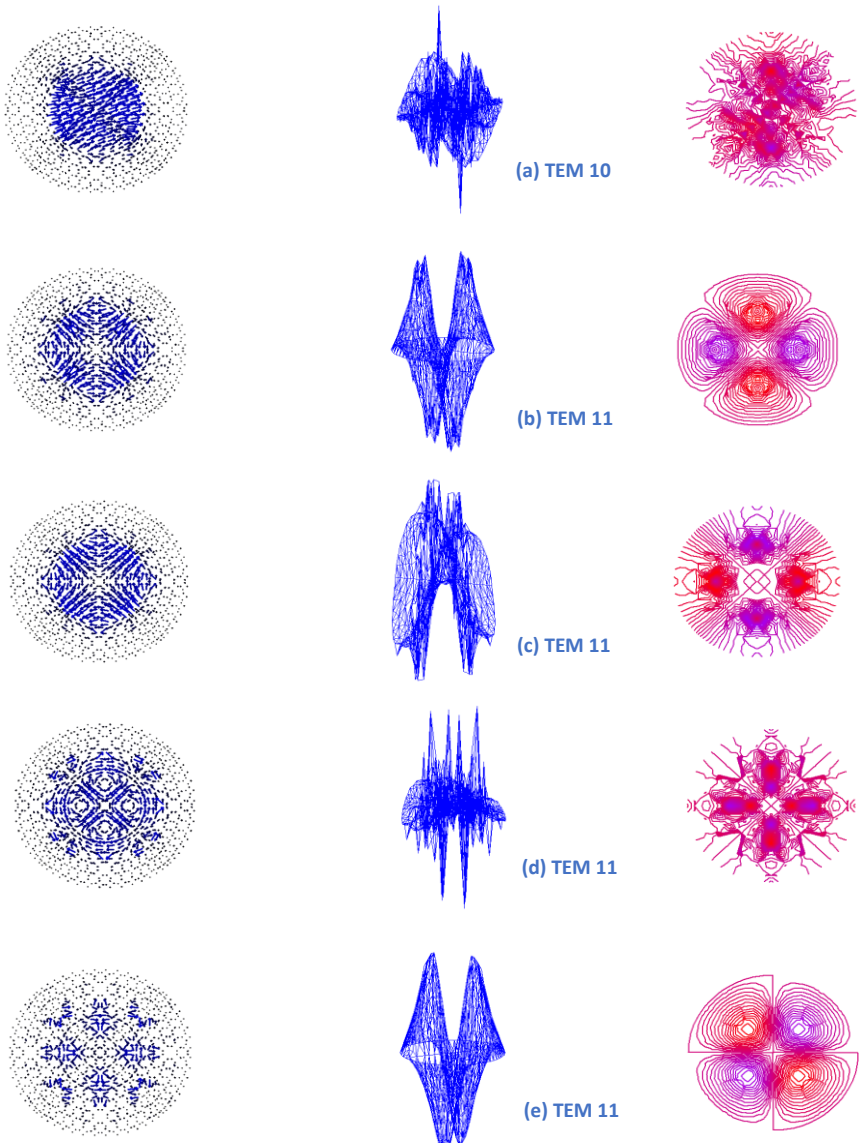


Figure 2: Schematic representation of TEM spectra

The eigenmode pairs of PCWDH obtained through the FEM method are shown in Figure 2. Spectra are expressed in TEM mode, which consists of an electric field vector, three-dimensional potential, and electric equipotential contours, respectively. The physical properties can be interpreted by eigenmodes of these spectra. The spectra describing the eigenmodes tend to be diffused, unlike conventional simple coaxial waveguides in which dielectric holes are excluded. In the FEM process, the calculation of TM and TE modes is determined by whether or not the edge and node components of the waveguide surface are included [5]. When obtaining the TM mode, the waveguide surface components are excluded from the eigen-matrix equation. This may result in lower order matrices for the TM case than those for the TE calculation. The spectra of Figure 3 are obtained by removing the surface components of the waveguide in the eigen-matrix equation. The purpose of this is to obtain the spectrum of the TM mode, but it can be seen that the TE mode is also mixed. Since the electric

field is a spatial gradient of potential, the presence of a normal component on the waveguide surface is suspected, as can be seen in Figure 3 (b). It cannot be concluded that the normal component to the surface can be excluded from the electric field of the TE mode. Therefore, these spectra can be determined to be a TEM mode that is a mixture of TM and TE modes. In the case of Figure 2 [a] spectrum, it has a shape similar to the fine eigenmode TEM 10 obtained from a coaxial waveguide. The spatial distribution of the electric field is similar, but comparing the equipotential lines, it is clearer in a conventional waveguide where dielectric structures are excluded. For Figure 2 (b) and (c), the spatial distribution of the electric field is similar. However, the equipotential lines of the electric field potential they represent are clearly different. These can be considered as TEM 11 modes, similar to TM and TE modes, respectively. And the spectra in Figure 2 [d] and [e] can be determined to be the eigenmode of TEM 11. The electric fields and equipotential lines they describe are clearly different. In the case of the electric field they describe, small scale components appear separately from the main peak at the boundary between the core and the cladding. Their appearance is believed to be the result of unstable interaction between the cladding and dielectric holes contained therein. However, considering the overall appearance of the spectrum, each eigenmode can be determined with TEM 11. The low order eigenmodes obtained by excluding the surface components of the waveguide from the eigen-matrix equation is described dominantly by TEAM 11.

Figure 3 is the spectrum of TE mode resulted from the eigen-matrix equation. In the process of calculation, boundary conditions are not applied to this equation. In other words, FEM calculations were performed without removing the edge and node elements of the waveguide surface. Therefore, the size of the eigen-matrix equations is as large as their number compared to the TM case. The electric field develops in a tangential direction at the core and cladding interface. As shown in Figure 3, the electric field does not go beyond the interface between the core and the cladding. The electric field is distributed entirely to the high-permittivity core, although some traces exist in the cladding region. This field is symmetrically distributed but exhibits a slightly deformed shape compared to a conventional waveguide in which dielectric holes are excluded. This is probably because the cladding and the dielectric hole do not complement each other. And it is assumed that it does not effectively contribute to eigenmode formation. As shown in Figure 3, the spectra are mainly composed of low-dimensional eigenmodes. In the case of Figure 3(a), the eigenmod can be determined to be TEM 10 by the electric field and equipotential. Although the electric potential is complex, the overall outline makes it possible to determine the eigenmode in this way. For the remaining spectra, it is difficult to determine the eigenmode simply by using the electric field or the distribution of the electric potential. These must be combined to determine the eigenmode, but their correlation is not so strong. Nevertheless, since they describe the same physical system, when the electric field is clear, the eigenmode is determined by this. And when the electric potential is clear, the eigenmode is assigned by it. The eigenmode of spectra Figure 3 (b) is determine by the electric potential to be TEM 20. The eigenmode of spectra Figure 3 (c) is assigned to be TEM 21 by the combination of electric field and electric potential. The eigenmode of spectra Figure 3 (d) is given by the electric field and electric potential to be TEM 22. The eigenmode of spectra Figure 3 (e) is determine by the electric field and electric potential to be TEM 31.

When compared to the conventional coaxial waveguide spectrum in which dielectric holes are excluded, the resolution of spectrum is generally not good. As can be seen in reference [6], the resolution of eigenmodes in conventional waveguides is clear, as can be estimated by the physical properties of their spectra. It seems that the dielectric hole inserted into the cladding has a negative effect on the formation of eigenmode in PCWDH. No matter how symmetrically the dielectric holes are arranged around the core, they have a negative effect on eigenmode formation. The relative dielectric constant values of the cladding and dielectric holes are much smaller compared to that of the core. The eigenmodes of electromagnetic waves formed in PCWDH are concentrated in the core region. However, the spectra shown in Figure 2 and 3 are complicated compared to those of coaxial waveguides excluding dielectric holes. This means that the actions of the cladding and the dielectric hole do not complement each other and have a negative effect on forming the eigenmode. Referring to these results and the recent report on photonic crystals, the use of this waveguide is no better than the conventional coaxial waveguide. In other words, it seems that photonic crystal waveguides are suitable for special purpose complex circuits than simple structures like the one in this study. If it is simply for propagation of the electromagnetic wave, a conventional coaxial waveguide is more efficient.

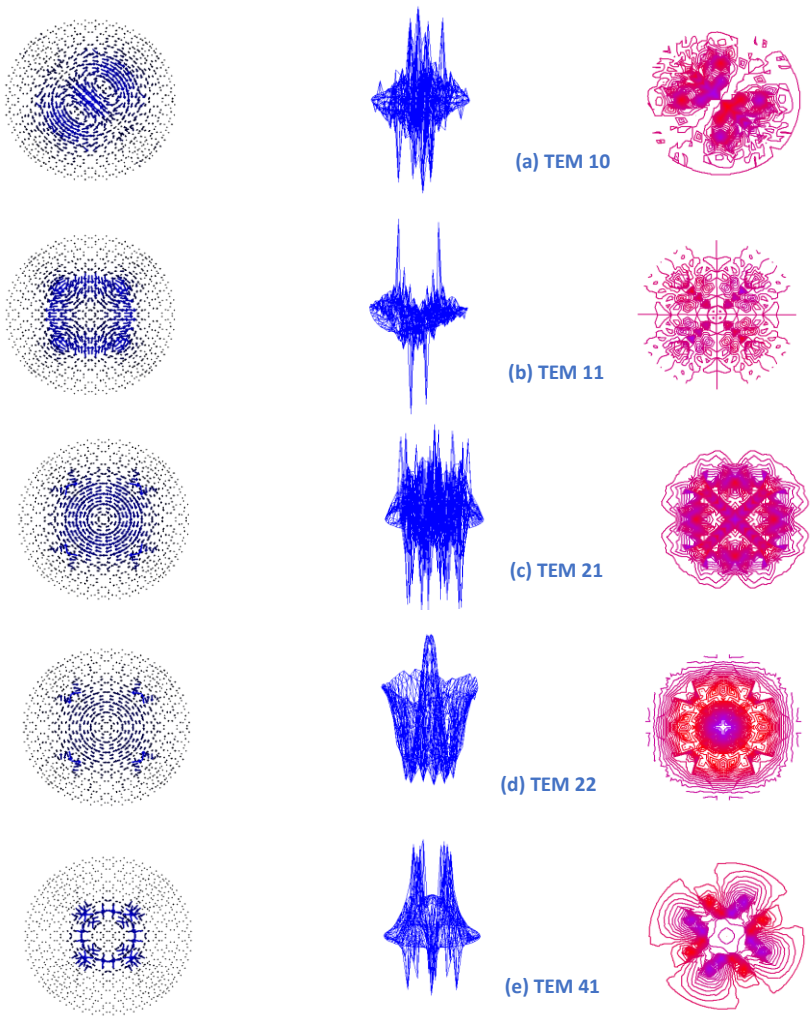


Figure 3: Schematic representation of TEM spectra.

CONCLUSION

In this study, the eigenmodes are calculated for PCWDH using the FEM. Overall, eigenmodes are not as good as conventional spectra regardless of electric field or potential. This is because the cladding and dielectric holes focus electromagnetic waves on the core, but do not complement each other and act negatively. This is understood to be because the dielectric holes act as defects even if they are arranged symmetrically around the core in the waveguide. It seems that photonic crystal waveguides are suitable for complex circuits of special purpose than simple structures like the one in this study.

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